The evaluative methods on shale gas productivity using the DFIT

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This is the Eternal Flame Waterfall, on Shale Creek, in Chestnut Ridge Park, near Buffalo, New York. A pocket of natural methane gas in an alcove below the waterfall seeps out through a fracture in the rocks.
1. Introduction

2. DFIT (diagonal fracture injection test)

3. Pre-closure analysis

4. After-closure analysis

5. Summary and future works
<table>
<thead>
<tr>
<th>Formation Type</th>
<th>Darcy Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone Formations</td>
<td>Milli-darcies</td>
<td>$1 \times 10^{-3}$ D</td>
</tr>
<tr>
<td></td>
<td>Micro-darcies</td>
<td>$1 \times 10^{-6}$ D</td>
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<td></td>
<td>Nano-darcies</td>
<td>$1 \times 10^{-9}$ D</td>
</tr>
<tr>
<td>Tight Formations</td>
<td>Micro-darcies</td>
<td>$1 \times 10^{-6}$ D</td>
</tr>
<tr>
<td>Shale Formation</td>
<td>Nano-darcies</td>
<td>$1 \times 10^{-9}$ D</td>
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</tbody>
</table>
The limit of conventional well test method for shale formation.

- Low permeability, Long transient time
- Build-up, Draw-down, flow test is impossible
- Needs for rapid test method for shale/tight formation.
  → Mini fracture test (DFIT)
- Effective permeability using DFIT (diagonal fracture injection test)
DFIT or Mini frac test

1. Perforation
2. Installation of pressure gauge
3. Injection
4. Shut-in and record

Ewens, 2012
PRE CLOSURE ANALYSIS

• Formation Breakdown Pressure
• Fracture Closure Pressure
• Instantaneous Shut in Pressure (ISIP)
• Fracture Gradient = ISIP / Formation Depth
• Net Fracture Pressure ($\Delta p_{\text{net}}$) = ISIP - Closure Pressure
• Fluid efficiency = $G_c/(2+G_c)$ : $G_c$ is the G-function time at fracture closure
• Formation Leak Off Characteristics

AFTER CLOSURE ANALYSIS

• Formation permeability ($k$)
• Reservoir pressure ($p_i$)
• Net Horizontal Stress (closure – pore pressure)
Research Trend

**Nolte (1979)**
- G-function and fracture pressure decline analysis

- Pressure dependent leak-off vs. G-function, \( \frac{dP}{dG} \), \( \frac{GdP}{dG} \) plot

**Gu et al. (1993), Nolte (1997), Benelkadi and Tiab (2004)**
- After closure time function, Impulse fracture test

**Soliman et al. (2005) / Craig and Blasingame (2006)**
- Short term test

**Meyer (2007)**
- Mass and momentum equation for 2D-fracture
PRE-CLOSURE ANALYSIS

Fracture Closure Pressure

Time

Bottomhole Pressure

Injection Rate

Cushion Pressure

Breakdown Pressure

ISIP

Reservoir Dominated

Fracture Closure Pressure

Linear Flow

Radial Flow

Nolte, 1982
Located in north eastern British Columbia

Horn River Group (Muskwa Fm., Otter Park Fm., Evie Fm.)

Approximately 2,500m below surface

Average 170m thick, Average TOC: 4.3%

Composed of siliceous, organic rich shale (high quartz content)
Injection data for Well A

0.48 0.50 0.52 0.54 0.56 0.58 0.60 0.62 0.64 0.66 0.68 0.70 0.72 0.74 0.76 0.78 0.80 0.82
Cum Time (h)
Definition of G-function

- **G function**: dimensionless time function relating shut-in time to total pumping time

\[
G(\Delta t_D) = \frac{4}{\pi} (g(\Delta t_D) - g_o)
\]

\[
g(\Delta t_D) = \frac{4}{3} \left[ (1 + \Delta t_D)^{1.5} - \Delta t_D^{1.5} \right]
\]  
(For low leak-off)

\[
g(\Delta t_D) = (1 + \Delta t_D) \sin^{-1}((1 + \Delta t_D)^{-0.5}) + \Delta t_D^{0.5}
\]  
(For high leak-off)

\[
\Delta t_D = \frac{t - t_p}{t_p}
\]

\[
g_o = \frac{\pi}{2}
\]  
(For high leak-off)

\[
g_o = \frac{4}{3}
\]  
(For low leak-off)
Pressure dependent leak-off -> Existence of fracture!
Oil base micro-imager
G-function analysis of Well-B

Pressure dependent leak-off
G-function analysis of Well-C

G-function

Normal leak-off
• It could be possible to find out the leak-off behavior and fracture related reservoir properties for shale formation by pre-closure analysis

• G-function analysis data and OBMI data were compared to validate the existence of natural fracture near well bore and reliable correlation is found with this methods.
AFTER CLOSURE ANALYSIS

Fracture Closure Pressure

Nolte, 1982
• Combining the continuity equation, the equation of motion, and the EOS

**Diffusivity eqn.**
\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial p}{\partial r} \right) = \frac{\phi \mu c_t}{k} \frac{\partial p}{\partial t}
\]

**Real gas law**
\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{p}{\mu z} \frac{\partial p}{\partial r} \right) = \frac{\phi \mu c_t}{k} \frac{p}{\mu z} \frac{\partial p}{\partial t}
\]

**Gas compressibility, pseudo state** \((\phi, \mu, z\text{ constant})\)

\[
m(P_{wf}) = m(P_i) - \frac{711QT}{kh} \left[ \ln t_a + \ln \left( \frac{k}{\phi \mu C_t r_w^2} \right) - 7.43173 + s' \right]
\]
**Nolte**

- **Linear flow**

\[ p_w(t) - p_i = C_L \sqrt{\frac{\pi \mu}{k\phi C_i}} F_L \]

- **Radial flow**

\[ p_w(t) - p_i = 251,000 \frac{Q_i \mu}{kht_c} F_{R1} \]

\[ m_{R1} = 251,000 \frac{Q_i \mu}{kht_c} \]

\[ kht_c = 251,000 \frac{Q_i \mu}{m_{R1} t_c} \]

\[ p_i = p_w(F_{R1} \to 0) \]

**Soliman-Craig**

- **Linear flow**

\[ p_w(t) - p_i = 31.05 \frac{V_{inj} \mu}{\phi C_i k h x_f^2} \left[ \frac{1}{t_p + \Delta t} \right]^{0.5} \]

- **Radial flow**

\[ p_w(t) - p_i = (1694.4) \frac{V_{inj} \mu}{kh} \left[ \frac{1}{t_p + \Delta t} \right] \]

\[ m_{R2} = (1694.4) \frac{V_{inj} \mu}{kh} \]

\[ kht_c = (1694.4) \frac{V_{inj} \mu}{m_{R2}} \]

\[ p_i = p_w \left( \frac{1}{t_p + \Delta t} \to 0 \right) \]
Linear and Radial flow plot for well A

Minifrac Linear (Nolte)

Minifrac Linear (Sollman-Craig)

Minifrac Radial (Nolte)

Minifrac Radial (Sollman-Craig)
Reservoir properties from 2 methods (well A)

- **Nolte method**
  - Permeability: 11.6 μd
  - Initial pressure for radial flow: 5,324 psi
  - Leak-off coefficient: $6.0519 \times 10^{-4}$ ft/min$^{1/2}$

- **Soliman-Craig method**
  - Permeability: 9.98 μd
  - Initial pressure for radial flow: 5,317 psi
  - Fracture half-length: 16.6 ft
Permeability estimation

\[ k = \frac{0.086 \mu_f \sqrt{0.01 p_z}}{\phi c_t \left( \frac{G_c E \rho_p}{0.038} \right)^{1.96}} \]

- \( \mu_f \): Viscosity of injected fluid (= 1 cp, assumption)
- \( p_z \): Net fracture extension pressure above closure pressure (9873 psi)
- \( G_c \): G-function closure time (= 32.705h)
- \( E \): Young’s modulus (= 3.35Mpsi)
- \( \rho \): Storage ratio (= 1)
- \( \phi \): porosity (= 0.04)
- \( C_t \): Total compressibility (= 5.09X10^{-5} /psi)

Calculate \( K = 4.4351 \mu \text{D} \)

<table>
<thead>
<tr>
<th>Case</th>
<th>G-function (Baree)</th>
<th>Nolte</th>
<th>Soliman</th>
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<tbody>
<tr>
<td>Well A(( \mu \text{D} ))</td>
<td>4.4351</td>
<td>11.6</td>
<td>9.98</td>
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</table>
Summary and further study

DFIT results in the Kiwigana shale formation were presented.

- The results have good consistency between other analytical methods and will be used for hydraulic fracturing job effectively.

- The need for the prolonged shut-in time is realized to analyze the radial flow regime in DFIT.

- Permeability estimation equation is useful for rough calculation.

- Many production characteristics of shale gas reservoir need to be monitored to correlate reservoir properties.

- Influence on adsorbed gas and stress dependent rock properties should be considered to evaluate more precisely.
Thank you for your attention!